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The J-MAPS Mission: Improvements to Orientation Infrastructure and Support for Space Situational Awareness

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[Abstract] The Joint Milli-Arcsecond Pathfinder Survey (J-MAPS) mission is a star mapping microsat mission proposed for launch in the 2011 timeframe. The primary objectives of J-MAPS are to generate star catalogs that are 15 times more accurate at current epoch (2007) and 100 times denser than those based on the Hipparcos mission, demonstrate the ability to measure pointing to 10 milliarcseconds (mas) and control pointing to 50 mas on-orbit with a microsat bus, and to mature and risk reduce technology for next generation attitude determination systems, and both down- and up-looking imaging systems. The instrument, a 15 cm aperture telescope with an 8k x 8k CMOS-Hybrid focal plane array, will observe stars to 1 mas mission accuracy down to 12th magnitude, with reduced accuracy to 15th magnitude. J-MAPS can also be used to observe resident space objects with extreme metric accuracy, with the potential to contribute significantly to the space surveillance network's ability to rapidly determine orbits, recover maneuvers, assess conjunctions and update the space object catalog. These capabilities, to be demonstrated on-orbit, will complement the capabilities of future systems and can actually serve as an SSA asset multiplier by reducing the individual target workload on these future systems, increasing overall target throughput.

I. Introduction

THE one, and heretofore only, astrometry mission flown in space was the European Space Agency's Hipparcos mission[1]. Hipparcos flew from 1989 to 1993, collecting very high accuracy astrometric (i.e., position, proper motion and parallax, or inverse distance) for approximately 118,000 stars, primarily in the brighter (0-7) magnitude range. The Hipparcos data continue to form the basis for star catalogs used in current, high-accuracy star trackers.

At mean observing epoch (i.e., 1991.25), the Hipparcos catalog would have had a mean accuracy of 1 milliarcsecond (mas)‡. Limitations imposed by both the accuracy of the Hipparcos measurements and the relatively short temporal baseline result in stellar proper motion uncertainties of approximately 1 mas. As a result, the mean star positional accuracy has degraded to approximately 17 mas in 2007.

For lower accuracy applications, this is not necessarily a problem. For higher accuracy applications, especially future applications, this degradation can impose significant constraints on future systems.

The Joint Milli-Arcsecond Pathfinder Survey (J-MAPS) is a proposed mission to re-observe all Hipparcos stars (as well as virtually all others down to around 14th magnitude) in order to correct this degradation and significantly reduce the rate of future degradation. J-MAPS is essentially a bright star space astrometry mission, designed to take advantage of a twenty-year baseline between Hipparcos and the 2010 epoch to generate new catalogs for future users that will be viable for decades.

II. Overview of the J-MAPS Mission

A mission concept study conducted in late 2005 to early 2006 produced a baseline design, cost and schedule estimates for J-MAPS. Figure 1 is a visualization of the baseline design developed as part of the concept study.

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‡ We note that 1 mas = 1/1000th of an arcsecond ≈ 4.8 nanoradians.
[5] This is equivalent to 1/50th—1/100th of a pixel centroiding.

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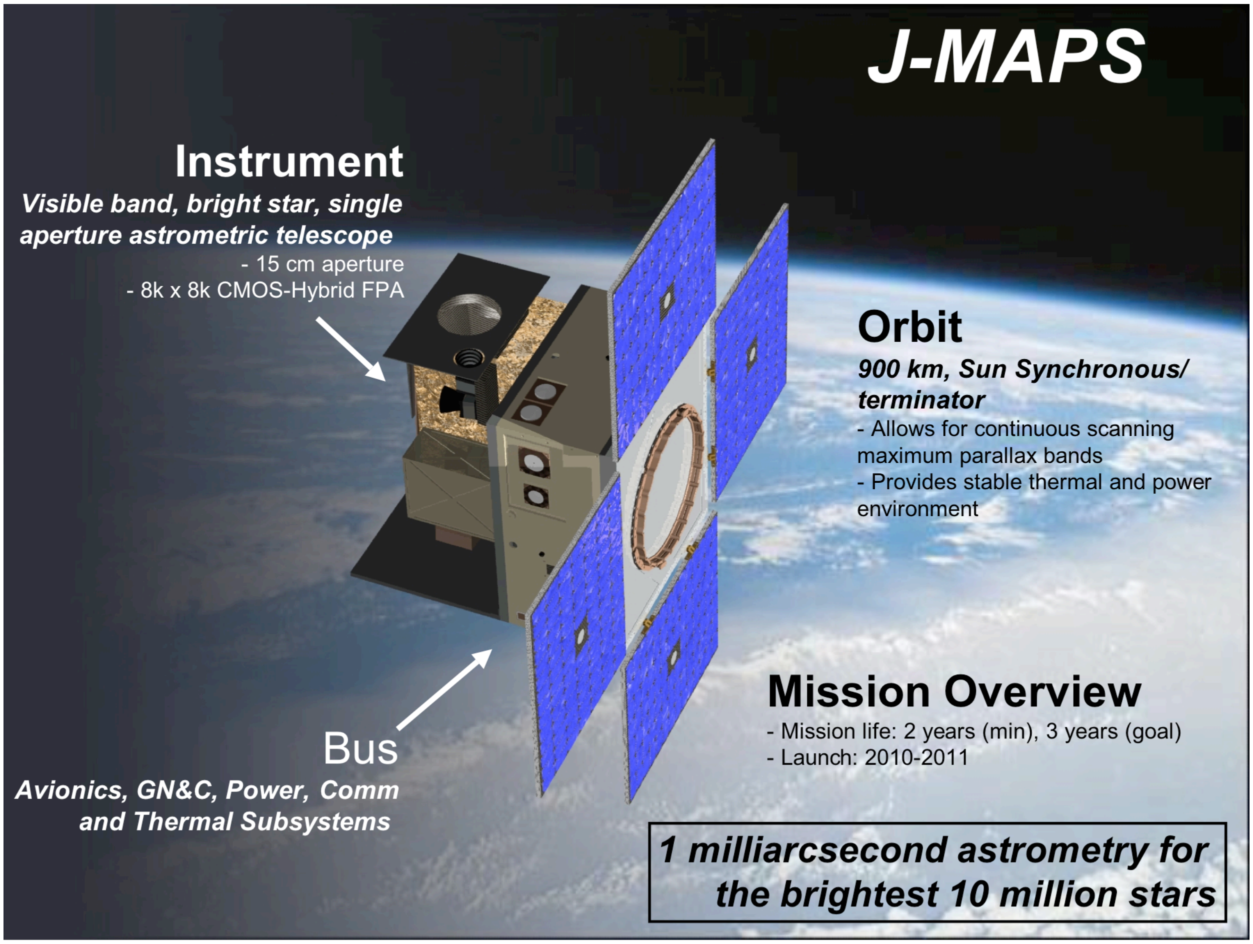

Figure 1. J-MAPS Concept Study Baseline Design.

J-MAPS consists of a single instrument deployed on a microsat bus. The instrument is essentially a very high accuracy star tracker fixed to the microsat bus, with pointing effected by orienting the bus. The instrument is operated in "step-stare" mode, with the instrument spending approximately 30 seconds imaging a single field on the sky, then moving to the next field. Over a single observing epoch (approximately one day), each star is observed four times. Over the course of the entire two to three year mission, each star is observed approximately fifty to seventy five times. The instrument is designed to measure star positions with 5-10 mas single measurement precision[5] with a resultant overall mission accuracy of 1 mas.

The baseline orbit is a 900 km Sun Synchronous Orbit (SSO) along the terminator. The instrument is affixed to the bus such that it preferentially observes stars near quadrature from the sun. This is desirable for parallax measurements (see fig. 2). The power system is sized so as to support a duty cycle of approximately 10% of total mission time outside this band.

The instrument consists of a 15-cm, f/25 extremely low distortion optical telescope coupled with an 8k x 8k CMOS-Hybrid focal plane assembly (FPA)[2] and supporting electronics. Each detector pixel subtends approximately 0.5 seconds of arc, and the instrument will have a 1.2° x 1.2° field of view (FOV). As a result, stellar point spread functions (PSF) will be sampled at around two pixels full-width at half-maximum (FWHM).

The CMOS-Hybrid FPA is, perhaps, the most technologically innovative aspect of the J-MAPS mission. It couples CCD-like performance with the flexibility, lower power and radiation hardness associated with monolithic CMOS FPAs[3,4]. For example, the J-MAPS FPA supports non-destructive read and random access windowing. The former allows the spacecraft to be guided directly from the instrument without interruption of science data collection, while the latter allows access to the entire FPA at potentially very high frame rates without the data rates or read noise penalties associated with CCD implementation of these capabilities.

Over the course of the J-MAPS mission, "windows" around each star (rather than the entire FPA) will be returned to the ground, along with the relevant housekeeping and metadata. The data will be reduced on the ground, and over the course of the mission, a comprehensive catalog providing position, proper motion, parallax and color data at high accuracy will be provided.

Previous catalogs such as Hipparcos are tied to the ICRF via a small number of radio reference "tie stars"; as a result, not only are Hipparcos star positions degrading, but the Hipparcos reference frame's tie to the ICRF is also degrading. In order to eliminate this source of error, the J-MAPS reference frame will be tied directly with the International Celestial Reference Frame (ICRF) by observing up to 100 quasi-stellar objects (QSOs, or "Quasars") that are also ICRF refernce sources.

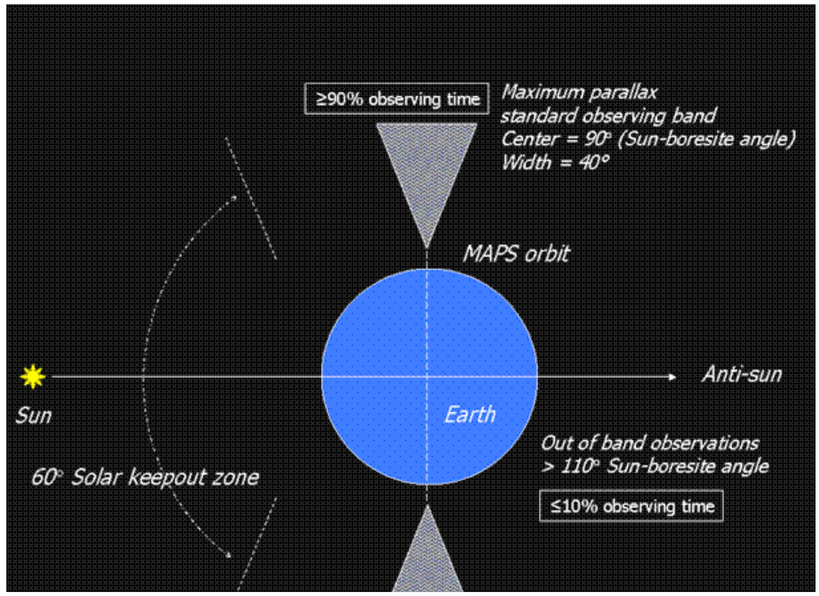

Figure 2. J-MAPS observing geometry.

III. SSA Applications

J-MAPS will support SSA in at least two different ways: First, J-MAPS will generate a high-density, high-accuracy star catalog of background reference stars. Second, by virtue of its unique design, it is capable of providing very high accuracy position measurements for a limited number of RSOs. The combination of the two of these will result in a capability of generating orbits of unprecedented accuracy for RSOs observed on-orbit by J-MAPS. The J-MAPS mission, while not designed explicitly for SSA, can demonstrate the SSA capability of space-based astrometric instruments. In the following two sections, we discuss each of these concepts in more detail.

A. Visible background reference catalog

The most direct impact of the J-MAPS mission on Space Situational Awareness applications will be to provide a reference catalog that future visible SSA assets can use for high metric precision measurements. Visible SSA assets derive orbits of geosynchronous (GEO) resident space objects (RSO) by determining their observed positions against the background reference stars. The high accuracy Hipparcos reference stars (the equivalent of ~3.5 m at 40,000 km in 2007) are relatively sparse, with only 2—3 stars per square degree on average. Many regions (e.g., near the celestial poles) have zero Hipparcos sources per square degree. Furthermore, many of these sources are relatively bright for SSA sensors (~10 astronomical magnitudes brighter than the RSOs), presenting significant dynamic range problems.

On the other hand, deep (i.e., faint object) catalogs such as USNO-B, are much denser, and provide more than sufficient stars in the required dynamic ranges, but suffer from accuracy limitations. USNO-B, for example, has a mean accuracy of 200 mas in the 15—20th magnitude range. This is equivalent to 50 meters error at GEO for the reference stars, a significant amount given future SSA accuracy goals.

J-MAPS will generate a reference catalog complete through 12th magnitude at the 1 mas level. This will provide 60 stars per square degree on average at an equivalent accuracy of 20 cm at GEO. J-MAPS will routinely observe down to 14th magnitude at reduced accuracy—3 mas, equivalent to 60 cm at GEO—resulting in 300 additional stars per square degree on average at reduced accuracy. Dynamic range capabilities for modern sensors should make a J-MAPS catalog relevant down to 18-19th magnitude at a minimum.

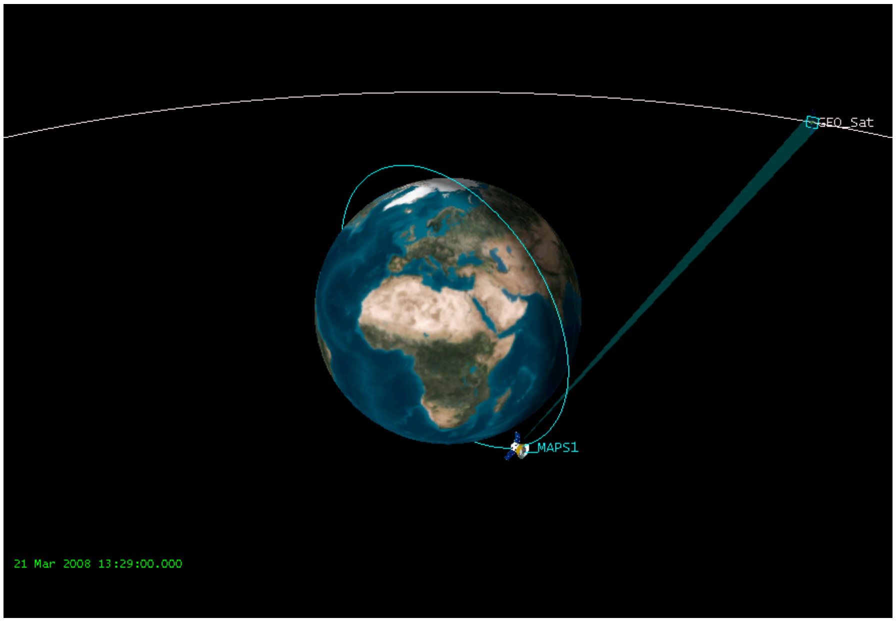

Figure 3. J-MAPS SSA concept visualization. J-MAPS satellite shown observing a GEO satellite.

B. High-Precision Position Measurement and Orbit Determination Demonstration

Unlike current and planned SSA sensors, J-MAPS is designed to excel at the determination of position stellar sources. Convention SSA sensors, on the other hand, trade some positional metric accuracy for a wider field of view, with the effect of increasing search rates and detection probability for fainter targets.. Designers for these other sensors have, in effect, chosen to give up some of their metric accuracy for the ability to search and detect.

With a 1.2° degree FOV, a PSFs spread over multiple pixels, and a 15 cm aperture, the J-MAPS instrument would not be considered an ideal, stand-alone SSA sensor. On the other hand, as a tasked asset that is part of a larger SSA architecture, J-MAPS has the poential to provide unique capabilities.

In a scenario such as the one shown in Fig. 3, J-MAPS, or a J-MAPS derivative, would be *tasked* by other assets to observe a specific target. The goal of these observations would be, for example, to convert a detection with a coarse orbit into a refined and highly accurate orbit. Alternately, one could conceive of a tasking related to sudden maneuver, in which case J-MAPS would be used to assess danger to high value blue assets and/or intent of the red or grey maneuvering asset. In both cases the detection and coarse tracking of the RSO is handled by other assets; use of J-MAPS capabilities is reserved for high metric accuracy position (angles) observations.

The J-MAPS instrument was designed to observe stars with a centroiding precision of 1/100th of a pixel. We can consider two observing modes for SSA observations: 1) sidereal track rate, and 2) GEO track rate. In the first case, the instrument is pointed such that the background stars are stationary; as a result, RSOs will generate streaks in the data. In the second mode, the instrument tracks a notional GEO target; as a result, the stars streak through the FOV while any GEO RSOs appear as stellar- (i.e., point-like) sources.

In the former case, the effective brightness of a J-MAPS detected RSO is limited to approximately 10-11th magnitude and brighter. In the latter mode, the J-MAPS detection brightness can go as deep as 15th magnitude. In both cases, we estimate the limiting precision of the observations will be at the 1/10th of a pixel (i.e., 50 mas) level. 50 mas is equivalent to approximately 10 meters at GEO. We thus estimate that J-MAPS can observe GEO objects of sufficient brightness with a single measurement position accuracy of approximately 10 meter.

In order to assess how useful J-MAPS observations would be to high-accuracy orbit determination, covariance simulations were run. These analyses generated orbit parameter error estimates based on J-MAPS single measurement accuracy combined with different observing scenarios. These scenarios consisted, in part, of:

- Scenario 1-B: A single "epoch" of twenty J-MAPS observations for a given target once every ten minutes over half a J-MAPS orbit (~50 minutes). Each observation consists of a full-frame image.
- Scenario 1-E: The same scenario, extended to two full J-MAPS orbits.
- Scenario 2-B: Single epochs using "rapid windowing" observing mode in which a tracking window follows the RSO as it transits the FPA. In this mode, approximately 1000 observations are available per epoch. Epochs are observed every ten minutes over a half J-MAPS orbit.
- Scenario 2-E: Rapid windowing extended over two J-MAPS orbits.

The simulation results are shown in figures 4—7.

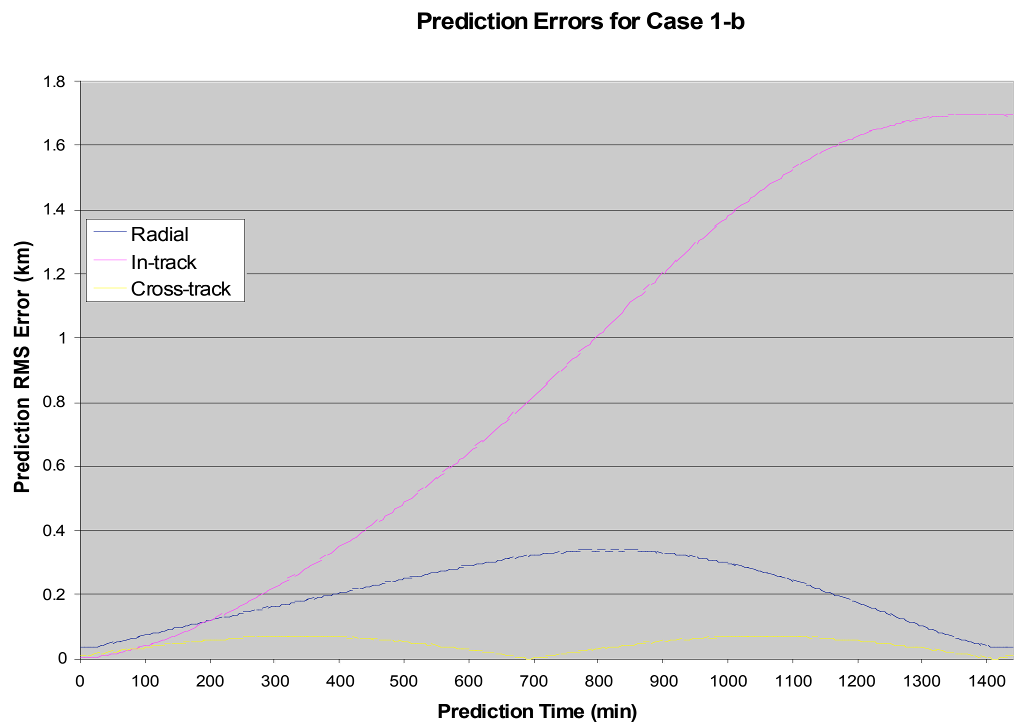

Figure 4. Orbital error propagation for J-MAPS observations of GEO satellite. Scenario 1-B: Full-frame images, 20 per epoch, 1 epoch every ten minutes, 50 minute span of observations.

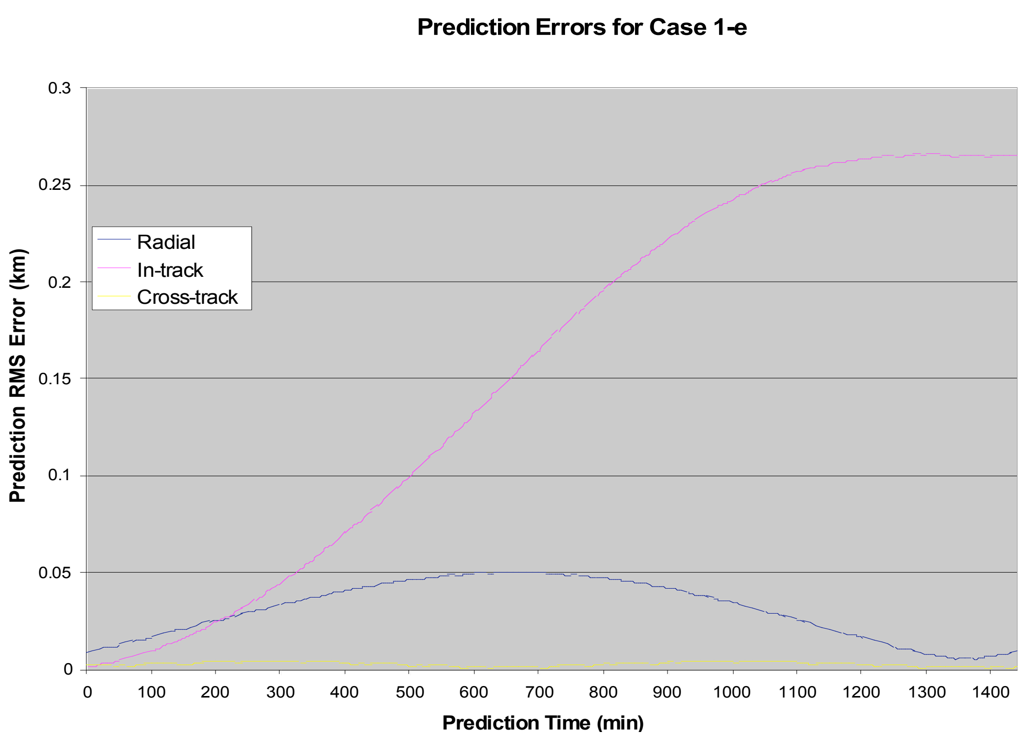

Figure 5. Orbital error propagation for J-MAPS observations of GEO satellite. Scenario 1-E: Full-frame images, 20 per epoch, 1 epoch every ten minutes, 200 minute span of observations.

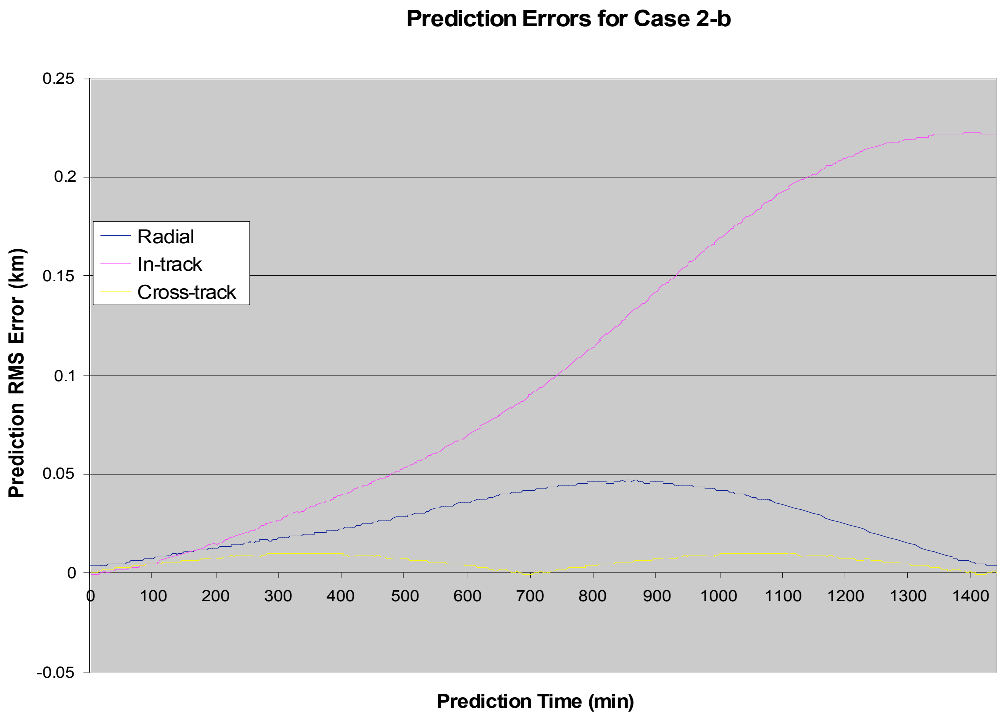

Figure 6. Orbital error propagation for J-MAPS observations of a GEO satellite. Scenario 2-B: rapid windowing, ten minutes per epoch, 50 minute total span of observations.

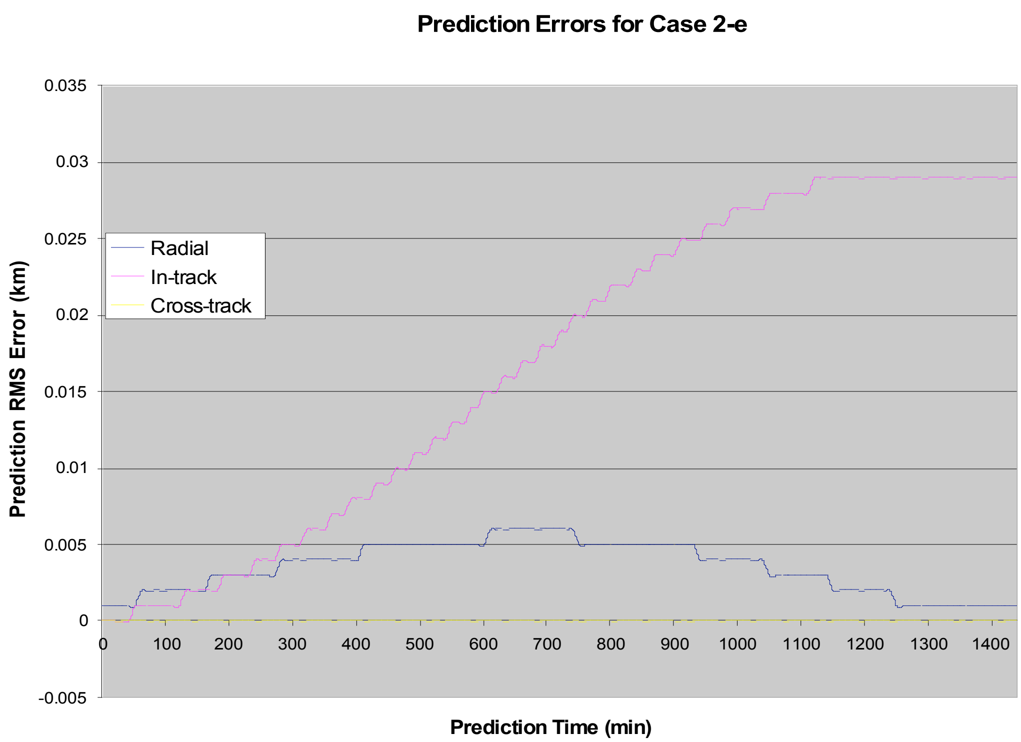

Figure 7. Orbital error propagation for J-MAPS observations of a GEO satellite. Scenario 2-E: rapid windowing, ten minutes per epoch, 200 minutes total span of observations.

The simulation results show that even for half an orbit using the most conservative observing mode (i.e., full frame), J-MAPS produces very high quality orbits (see fig. 4). At five hours, the orbits have degraded to a total error of approximately 200 m, and after ten hours, the degradation is 600 m, and after a full day, the orbit is accurate to approximately 1.7 km.

Observing over two rather than a half J-MAPS orbit (fig. 5) significantly increases the accuracy of the derived orbit. After five hours, the orbit is accurate to less than 50 m; after ten hours, to less than 150 m; and after one day, the orbits are accurate to approximately 250 m.

The "rapid windowing" mode is even more promising. The half-orbit scenario (fig. 6) using this mode is more accurate than the two-orbit scenario using the full-frame observing mode. The two-orbit scenario (fig. 7) achieves accuracies that are at the level (10-30 m) of the size of some GEO objects, thus they are, in principle, as good as one could hope to achieve without resolving the RSOs themselves. We note that the predictions presented here for rapid windowing assume no correlation between frames. While this assumption was also adopted for the full fram observations, it is much more problematic for the rapid windowing mode given the fact that we propose to use fifty times as many observations for the latter observations. Until this assumption can be tested in space with actual observations, the results—especially figs. 6 and 7—are limiting cases that portray how well one of these sensors *could* perform.

Accuracies at this level are not achievable by other SSA sensors. There are a variety of different SSA applications that would benefit from these capabilities: rapid orbit determination and catalog maintenance for high value RSOs, conjunction assessment, and maneuver detection and recovery. In addition, J-MAPS is significantly more efficient than other assets at taking these specific types of measurements. As such, use of J-MAPS for high-accuracy orbit determination rather than other assets would allow them to concentrate their resources on, for example, increased target throughput rather than spending significant resources on single targets. In this way, J-MAPS could act as a significant "force multiplier."

IV. Summary and Conclusion

The J-MAPS mission is intended to fly in the 2010/2011 timeframe. The goal of J-MAPS is to collect bright star (2-12th magnitude) position, motion, parallax and color data at high accuracy (~1 mas) in order to completely update and densify the current bright star catalog. This catalog will not only benefit high accuracy orientation users, but also the entire SSA community by developing an optical reference grid that is accurate at the 20 cm level with mean stellar densities at the ~100 stars per square degree level.

In addition, the J-MAPS instrument could be used, on orbit, to demonstrate the orbit determination capabilities of a dedicated, space-based astrometric sensor. J-MAPS could, in principle, demonstrate orbit determination for sufficiently bright targets with accuracies approaching the physical size of these targets. This is relevant for two reasons: first, J-MAPS could be transitioned to full-time SSA use after the conclusion of its primary mission. If there is sufficient interest in this option, accommodations should be made now to ensure that J-MAPS will support these needs well into the future. Second, the SSA capabilities demonstrated by J-MAPS could form the basis for future, dedicated SSA instruments or spacecraft but which employ the basic design and concepts that J-MAPS will demonstrate.

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